



TECHNICAL REPORT

JOINT INDUSTRY PROJECT

RELIABILITY ANALYSIS OF DEEPWATER PLATE ANCHORS

PROJECT SUMMARY (TECHNICAL REPORT TR 3)

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DET NORSKE VERITAS



TECHNICAL REPORT

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Summary:

A reliability analysis of plate anchors in clay has been performed with the objective to calibrate the partial safety factors of a simplified design code applicable to both drag-in type and push-in type plate anchors. The design code subject to calibration is a somewhat modified version of the procedure published as DNV Recommended Practice RP-E-302 for drag-in plate anchors.

The reliability analysis disregards the anchor installation effects, which are anchor type specific. Such effects are addressed separately and become part of the overall design issues, which emphasises the important inter-relationship between design and installation of plate anchors.

It is proposed to revise the safety format in the design code for drag-in plate anchors in DNV RP-E302 from currently two partial safety factors to a single partial safety factor on the anchor resistance, which is the design code subject to calibration. The resulting calibrated design code is applicable to both drag-in type and to push-in type plate anchors.

Recommendations for further work are given, although this will not be covered by the current project budget.

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1 CONCLUSIVE SUMMARY

1.1 General

A reliability analysis of plate anchors in clay has been performed with the objective to calibrate the partial safety factors of a simplified design code applicable to both drag-in type and push-in type plate anchors. The design code subject to calibration is a somewhat modified version of the procedure published as DNV Recommended Practice RP-E-302 /1/ for drag-in plate anchors.

The reliability analysis disregards the anchor installation effects, which are anchor type specific. Such effects are addressed separately and become part of the overall design issues, which emphasises the important inter-relationship between design and installation of plate anchors.

It is proposed to revise the safety format in the design code for drag-in plate anchors in /1/ from currently two partial safety factors to a single partial safety factor on the anchor resistance, which is the design code subject to calibration. The resulting calibrated design code is applicable to both drag-in type and to push-in type plate anchors.

Recommendations for further work are given, although this will not be covered by the current project budget.

1.2 Design code

The design code subject to calibration may briefly be described as follows:

With the above-mentioned changes to the safety format, the design anchor resistance R_d is expressed as

$$R_d(z_i) = \frac{R_C(z_i)}{\gamma_m} = \frac{R_{cy}(z_i)}{\gamma_m} = \frac{R_S(z_i) \cdot U_{cy}}{\gamma_m} \quad (1.1)$$

where γ_m will account for the uncertainties covered by the two partial safety factors in the current version of DNV RP-E302 /1/, see Section 3.2 for explanation of symbols.

The limit state function to satisfy is

$$R_d - T_d \geq 0 \quad (1.2)$$

in which the design line tension T_d is given by

$$T_d = T_{C-mean} \cdot \gamma_{mean} + T_{C-dyn} \cdot \gamma_{dyn} \quad (1.3)$$

1.3 Reliability analysis

The reliability analysis is applied to twelve test cases as listed in Table 5-1. The test cases include

- water depths from 1,000m to 2,000m,



- environmental conditions for the Gulf of Mexico and Haltenbanken,
- semisubmersible and ship with taut mooring system (TMS), and
- soil conditions given as four profiles covering both single layer and two-layer clay, in the latter case with the anchor assumed to penetrate into the underlying overconsolidated layer.

Preceding the full-scope reliability analysis, a pilot reliability was carried out for a single set of boundary conditions, thus providing the possibility to identify which parameters govern the results of the reliability analysis and where emphasis should be placed in the planning of the more detailed analysis.

In the full-scope reliability analysis the following eight parameters are modelled as stochastic variables:

$s_{u,anchor}$	intact undrained shear strength, as modelled
η	empirical reduction factor in expression for anchor resistance
U_{cy}	cyclic loading factor (factor on static strength)
N_{eq}	equivalent number of cycles to failure
C_{OCR}	random factor for representation of uncertainty in OCR
F	applied line load
U_F	model uncertainty factor on line tension, and
U_R	model uncertainty factor on anchor resistance

1.4 Calibration

As a basis for the code calibration the following three consequence classes are considered, all applicable for both ULS and ALS:

- 0** Tentatively, CC0 is reserved for platforms which are evacuated in severe weather, and are at a safe (large) distance from adjacent platforms and pipelines. (CC0)
- 1** Failure is unlikely to lead to unacceptable consequences such as loss of life, collision with an adjacent platform, uncontrolled outflow of oil or gas, capsizing or sinking (CC1).
- 2** Failure may well lead to unacceptable consequences of these types (CC2).

For these three consequence classes the prescribed target annual probabilities of failure $P_{F,t}$ are 10^{-3} , 10^{-4} , and 10^{-5} , respectively.

The probability of failure is calculated for a series of values of the plate depth. For each limit state, consequence class, and design case, the plate depth corresponding to the required target probability $P_{F,t}$ is found by interpolation on these results. It may be denoted by $z_{plate}(P_{F,t})$. The characteristic resistance at this depth is then $R_C[z_{plate}(P_{F,t})]$ from Equation (5.1). An estimate of the partial safety factor γ_m for an individual design case is simply given by

$$\gamma_m = \frac{T_d}{R_C[z_{plate}(P_{F,t})]} \quad (1.4)$$

The calculation is organised differently when calibrating over the whole set of design cases. The calibration for one limit state and one consequence class is considered. A trial value of γ_m is then



chosen initially. The plate depths required to satisfy the design equation may then be denoted $z_{plate,i}(\gamma_m)$ where the subscript i refers to the i th design case. The corresponding probabilities $P_{F,i}(\gamma_m)$ are obtained by interpolation on the reliability results. The value of γ_m is chosen which overall minimises the deviations $P_{F,i}$ from the target $P_{F,i}$ over the set of design cases.

The results of the partial safety factor calibration according to the above procedure are presented in Table 1-1. The partial safety factors for load, γ_{mean} and γ_{dyn} , shown in brackets, are for this calibration set equal to the values prescribed in /1/. For CC0 tentative values have been assumed, since this consequence class has not been subject to calibration before.

Table 1-1 Calibrated partial safety factor γ_m for anchor resistance

Limit State	ULS			ALS		
Consequence Class	0	1	2	0	1	2
γ_{mean} (prescribed)	(1.00)	(1.10)	(1.40)	(1.00)	(1.00)	(1.00)
γ_{dyn} (prescribed)	(1.10)	(1.50)	(2.10)	(1.10)	(1.10)	(1.25)
γ_m	1.36	1.42	1.39	0.71	0.99	1.29

It is noted that the achieved failure probabilities show some variability over the scope of the code as represented by the 12 test cases, although these failure probabilities are the result of a minimisation of this variability.

One goal of the code calibration is to develop partial safety factors that lead to as uniform a safety level as possible. In the future, one might therefore want to either refine the code format or reduce the scope of code in order to obtain a more uniform safety level. An investigation has shown that the safety level will become more uniform if the test cases defined for a ship on Haltenbanken are removed from the scope of code, leaving the scope of code represented by test cases defined on the basis of semisubmersibles only. A similar improvement may be obtained if the characteristic soil strength value becomes redefined from its present value equal to the mean to some lower-tail quantile.

Other means for improvement of the calibration are also recommended, although such additional work is not covered by the current project budget.

1.5 Design issues for plate anchors

It has been a recognition from the very start of this project that plate anchors cannot be designed without due consideration of the anchor installation effects. The report on design issues for plate anchors in clay /2/ therefore addresses not only the design code, but also the effect of keying and rotation of the anchor before it is in the position for acting as an efficient component of a mooring system.

The revised design code for plate anchors, identical to the code subject to calibration, is described in all details in /2/, and tentative recommendations for assessment of the target penetration depth of plate anchors are given.

1.6 Characterisation of plate anchors

Currently, two main types of plate anchors are used in deepwater mooring systems, namely the drag-in type described in /3/ and the push-in type described in /4/, both with contributions from the anchor manufacturers.



2 INTRODUCTION

2.1 About the Project

2.1.1 Participants

The project "Reliability Analysis of Deepwater Plate Anchors" is organised as a joint industry project (JIP). Financial funding from the following eight participants is gratefully acknowledged:

BP Exploration Operating Company Limited (BP), United Kingdom

Den norske stats oljeselskap a.s (STATOIL), Norway

Det Norske Veritas AS (DNV), Norway

Health & Safety Executive (HSE), United Kingdom

Petrobras Europe Limited (Petrobras); United Kingdom

Norwegian Petroleum Directorate (NPD), Norway

Minerals Management Services (MMS), USA

Norske Conoco AS (Conoco), Norway

2.1.2 Brief Description of Project

The objectives of this JIP are as follows:

- to perform a reliability analysis of drag-in type plate anchors utilising the experience from the previous JIP /5/ /6/
- to incorporate also the push-in type plate anchors in the reliability analysis utilising the similarities between the pullout resistance of the drag-in and the push-in types of plate anchor, but accounting for the differences between the anchor-specific installation effects on the pullout resistance
- to use the reliability analysis in the calibration of a simplified design code for both types of plate anchors
- to quantify the partial safety factors for use in the DNV Recommended Practice No. RP-E302 for design and installation of drag-in plate anchors, and
- to quantify the partial safety factors for use in the design of push-in type plate anchors as related to a tentative and simplified design code for such anchors.

The target reliability level will be defined after comparative analyses between the calibrated design equation and a wide range of likely design cases from practical design. The intention is then to set the target reliability level such that it is in reasonable harmony with the safety level that has been found acceptable for the type of structures covered by the agreed scope for the calibration.

The reliability analysis for drag-in plate anchors, will be preceded by a pilot reliability analysis, which will provide the basis for detailed planning of the full scope reliability analysis of both drag-in and push-in type plate anchors. The installation phase of push-in plate anchors will be



subject to separate studies based on the information available about this type of plate anchors, e.g. project-related installation scenarios or results from controlled anchor tests either onshore or offshore.

Results from a great number of in-house drag-in plate anchor tests were used in the development of the DNV Recommended Practice for drag-in plate anchors, RP E-302.

2.1.3 Project Organisation

In DNV the project team consists of Rune Dahlberg (Project Manager), Pål J. Strøm, Torfinn Hørte and Knut O. Ronold with Jan Mathisen and Knut Arnesen as Verifiers and Øistein Hagen as QA Responsible. Kim J. Mørk is Head of Section and Project Responsible.

The Steering Committee, composed of one representative from each participant with Asle Eide from STATOIL as Chairman, contributes to a validation of the final products from the project by approving plans and reviewing and commenting on the Draft Final Reports.

2.2 The Present Report

This report provides a summary of the work performed in the joint industry project on *Reliability Analysis of Deepwater Plate Anchors* and the results achieved, as documented in the issued interim and technical reports.



3 ABBREVIATIONS, SYMBOLS AND TERMS

3.1 Abbreviations

ALS	Accidental damage Limit State
DSS	Direct Simple Shear
TMS	Taut Mooring System (system with fibre rope lines)
ULS	Ultimate Limit State
CC	Consequence Class

3.2 Symbols and explanation of terms

Symbol	Term	Explanation of term
A_{plate}	Anchor plate area	Based on manufacturer's data sheet.
C_{OCR}	Unit mean random factor	Factor on predicted OCR to account for uncertainty and variability in OCR
CoV	Coefficient	Coefficient of variation (statistical)
d_c	Factor	Depth factor related to determination of $(N_c)_{shallow}$
F	Applied load	Used in the reliability analysis
g	Limit state function	Function of all stochastic variables included in the reliability analysis
η	Empirical factor	Reduction factor, related to N_c , derived from field tests
γ_m	Partial safety factor on $R_{cy}(z_i)$	Accounts for the uncertainty in - $s_u(z_i)$ as it affects $R_s(z_i)$, - the cyclic test data as they affect U_{cy} , - the prediction method and the analytical model
γ_{mean}	Partial safety factor on T_{C-mean}	Accounts for the uncertainty in the mean line tension
γ_{dyn}	Partial safety factor on T_{C-dyn}	Accounts for the uncertainty in the dynamic line tension
H_s	Significant wave height	Used in the calculation of $\tau_{f,cy}$
K_{OCR}	Adjustment factor	For correction of U_{cy} for effect of OCR
k	Undrained shear strength gradient	Average gradient between seabed intercept $s_{u,0}$ and shear strength at installation depth $s_u(z_i)$, or within the respective clay layer in layered clay (k_1, k_2, \dots)
k	Constant	Used to express the standard deviation σ_{su} of s_u
N_c	Bearing capacity factor for clay	Recommended value for deep penetration is $N_c=12.0$.
$(N_c)_{shallow}$	Bearing capacity factor for clay	N_c -factor for the shallow zone, $z_i < 4.5 W_F$, which accounts for the depth effect
N_{eq}	Equivalent number of cycles to failure	The number of cycles at the constant cyclic shear stress that will give the same effect as the actual cyclic load history
OCR	Overconsolidation ratio	Ratio between maximum past and present effective vertical stress on a soil element



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Symbol	Term	Explanation of term
P_F	Failure probability	Associated with the anchor failure state
R	Anchor resistance	Resistance in the line direction at the line dip-down point, determined for the anchor penetration depth $z_i = z_{plate}$
r	Function	Includes all stochastic variables envisaged for the anchor analysis
R_C	Characteristic anchor resistance	$R_C(z_i) = R_S(z_i) \cdot U_{cy} = R_{cy}(z_i)$
R_d	Design anchor resistance	$R_d(z_i) = R_C(z_i) / \gamma_m = R_{cy}(z_i) / \gamma_m$
ΔR_{cy}	Cyclic loading effect	Depends on extreme line tension history and soil characteristics, added to R_S
R_S	Static pullout resistance	Anchor resistance calculated with the static undrained shear strength $s_u = s_{u,D}$
R_{cy}	Cyclic anchor resistance	Includes both static and cyclic anchor pullout resistance
s_c	Plate shape factor	Related to N_c
s_u	Intact (static) undrained shear strength	For drag-in plate anchor analysis the DSS strength $s_{u,D}$ is assumed to be most representative
σ_{su}	Standard deviation	Standard deviation of s_u
$s_{u,D}$	Undrained shear strength	DSS static, intact, undrained shear strength
Δs_u	Change in s_u at $z_i = z_l$	Step change in s_u at layer boundary in a 2-layer profile
$s_{u,mean}$	Mean undrained shear strength	Accounts for variation in s_u across a layer boundary and within the volume of soil affecting the anchor resistance, depth interval $3W_F$, with centre at $z_i = z_{plate}$
τ_a	Average shear stress	↑ Used in connection with cyclic DSS tests
$\tau_a/s_{u,D}$	Average shear stress level	↓
T_d	Design line tension	With specified partial safety factors γ_{mean} and γ_{dyn} included
T_{d-mean}	Design mean line tension	With specified partial safety factor γ_{mean} included
T_k	Keying load	Load required to rotate the plate to a position creating 'close to' normal loading
U_{cy}	Cyclic loading factor	$U_{cy} = (1 + \Delta R_{cy}/R_S)$, where ratio $\Delta R_{cy}/R_S$ expresses the effect of loading rate and cyclic degradation on R_S
U_{su}	Statistical variable	Standard normally distributed variable for uncertainty in shear strength
W_F	Plate width	Shortest side of plate
z	Depth below seabed	
z_{calc}	Calculated penetration depth	From design calculations ($z_{calc} = z_{plate}$)
z_l	Depth to layer boundary	From sea bed to layer boundary No. 1
z_i	Installation penetration depth	At end of penetration, and after rotation of anchor into position for normal loading, z_i refers to centre of plate area ($= z_{plate}$).
z_{min}	Minimum penetration depth	To ensure deep embedment (deep failure), $z_{plate} > 4.5W_F$ below seabed and $z_{plate} > 1.5W_F$ below layer boundary
z_{plate}	Depth of plate	Reference depth for calculation of $s_{u,I}$ and $s_{u,III}$ ($z_i = z_{plate}$)
z_t	Target penetration depth	Accounts for loss of penetration depth Δz_k and Δz_f

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Symbol	Term	Explanation of term
Δz_k	Keying distance	Loss in penetration depth due to anchor keying and rotation
Δz_f	Failure displacement	Loss in penetration depth due to anchor failure displacement



4 DELIVERABLES

4.1 Technical Reports

The following *Technical Reports* have been issued, see /7/, /2/, and /8/ (this report), respectively:

- TR 1 *Reliability analysis of plate anchors*
- TR 2 *Design issues for plate anchors*
- TR 3 *Project summary*

4.2 Interim Reports

In addition, the following *Interim Reports* have been issued, see /3/, /4/, /9/, and /10/, respectively:

- IR 1-1 *Characterisation of drag-in plate anchors*
- IR 1-2 *Characterisation of push-in plate anchors*
- IR 2 *Pilot reliability analysis of drag-in plate anchors¹⁾*
- IR 3 *Basis for reliability analysis of drag-in plate anchors¹⁾*

¹⁾ Covers also push-in type plate anchors



5 SUMMARY OF WORK PERFORMED

5.1 Design code subject to calibration

5.1.1 Characteristic anchor resistance

The characteristic resistance R_C of a plate anchor at penetration depth z_i in a layered clay is given by the following general equation

$$R_C(z_i) = N_c \cdot s_c \cdot \eta \cdot s_{u,mean}(z_i) \cdot A_{plate} \cdot U_{cy} = R_S(z_i) \cdot U_{cy} \quad (5.1)$$

in which

$$R_S(z_i) = N_c \cdot s_c \cdot \eta \cdot s_{u,mean}(z_i) \cdot A_{plate} \quad (5.2)$$

is the characteristic static resistance, and

$$U_{cy} = \frac{\tau_{f,cy}}{s_u} \quad (5.3)$$

is the cyclic loading factor, defined as the ratio between the cyclic shear strength $\tau_{f,cy}$ and the static undrained shear strength s_u . In the reliability analysis and code calibration, s_u is assumed to be the DSS undrained shear strength $s_{u,D}$. The characteristic value to be used for U_{cy} is dealt with later.

The bearing capacity factor N_c is set equal to 12.0 for 'deep' failure, which takes place at penetration depths greater than $4.5 W_F$ below the seabed, as prescribed in /1/. For penetration depths less than $4.5 W_F$, the plate anchor is in the 'shallow' failure zone, where the maximum value of N_c cannot be counted on. Various expressions exist for the depth factor d_c that accounts for the change in N_c within the 'shallow' failure zone. An expression for $N_c = (N_c)_{shallow}$ that accounts for the depth effect in the 'shallow' failure zone is given in /7/. In the reliability analysis the anchor is assumed to be in the 'deep failure' zone.

The mean undrained shear strength $s_{u,mean}$ accounts for the variation in s_u within the volume of soil influencing the anchor resistance at failure, the extent of this volume being a function of the plate width W_F . The radius of the influenced soil volume is set equal to $1.5 \cdot W_F$ in the reliability analysis.

As an alternative to the expression in Eq. (5.1) the characteristic resistance may be expressed as the cyclic resistance R_{cy} , by replacing $s_{u,mean}$ with the cyclic shear strength $\tau_{f,cy}$, i.e.

$$R_C(z_i) = R_{cy}(z_i) = N_c \cdot s_c \cdot \eta \cdot \tau_{f,cy}(z_i) \cdot A_{plate} \quad (5.4)$$

5.1.2 Proposed change in code format

It is proposed to change from the current two partial safety factor format on the anchor resistance to a single partial safety factor format in DNV RP-E302 /1/.

The design anchor resistance R_d then becomes



$$R_d(z_i) = \frac{R_C}{\gamma_m} = \frac{R_{cy}(z_i)}{\gamma_m} = \frac{R_s(z_i) \cdot U_{cy}}{\gamma_m} \quad (5.5)$$

where γ_m will account for the uncertainties covered by the two partial safety factors in the current version of DNV RP-E302 /1/. One reason for this change in code format is that the cyclic loading effect is not large enough to warrant a separate partial safety factor. Another reason is that there is a growing recognition in the offshore industry that the cyclic shear strength rather than the intact shear strength should be used as the characteristic strength when designing offshore foundations governed by wave loading, ref. gravity base foundations and axially loaded piles.

The design inequality to satisfy is

$$R_d - T_d \geq 0 \quad (5.6)$$

where T_d is given by

$$T_d = T_{C-mean} \cdot \gamma_{mean} + T_{C-dyn} \cdot \gamma_{dyn} \quad (5.7)$$

The design mean tension is $T_{d-mean} = T_{C-mean} \cdot \gamma_{mean}$. The design normalised average stress level is

$$\frac{\tau_a}{s_{u,D}} = \frac{T_{d-mean}}{T_d} \cdot U_{cy} \quad (5.8)$$

The characteristic cyclic loading factor U_{cy} is to be taken as

$$U_{cy} = K_{OCR} \left(OCR, \frac{\tau_a}{s_{u,D}} \right) \cdot \mu_{U_{cy}} \left(\frac{\tau_a}{s_{u,D}} \right) \quad (5.9)$$

in which $\mu_{U_{cy}}$ is the expected value of the cyclic loading factor and K_{OCR} is an adjustment factor to account for effect of the overconsolidation ratio OCR. Both factors are functions of $\tau_a/s_{u,D}$. For details about these factors, see /7/. Note that the solution for the characteristic value U_{cy} by Eqs. (5.8) and (5.9) is iterative. The convergence is fast.

5.2 Reliability analysis and code calibration

5.2.1 General

The reliability analysis is applied to twelve test cases as listed in Table 5-1. The test cases include

- water depths from 1,000m to 2,000m,
- environmental conditions for the Gulf of Mexico and Haltenbanken,
- semisubmersible and ship with taut mooring system (TMS), and
- soil conditions given as four profiles covering both single layer and two-layer clay, in the latter case with the anchor assumed to penetrate into the underlying overconsolidated layer.

**Table 5-1 Specification of test cases¹⁾**

Test Case No.	Soil ²⁾⁴⁾	Platform type ³⁾	Environment	Water depth (m)
1	<u>Profile No. 1</u> 1 layer, $s_{u,0} = 3$ kPa OCR=1, $k_I = 1.0$ kPa/m	Semisubmersible	Gulf of Mexico	1,000
2	<u>Profile No. 2</u> 1-layer, $s_{u,0} = 5$ kPa OCR=1, $k_2 = 1.5$ kPa/m	Semisubmersible	Gulf of Mexico	1,000
3	<u>Profile No. 3</u> 2 layers, $s_{u,0} = 5$ kPa OCR=1, $k_2 = 1.5$ kPa/m OCR>1, $k_3 = 5 k_2$ $\Delta s_u = 14$ kPa at $z = z_I = 14$ m	Semisubmersible	Gulf of Mexico	1,000
4	<u>Profile No. 4</u> 2 layers, $s_{u,0} = 5$ kPa OCR=1, $k_2 = 1.5$ kPa/m OCR>1, $k_4 = 0$ $\Delta s_u = 94$ kPa at $z = z_I = 14$ m	Semisubmersible	Gulf of Mexico	1,000
5	Profile No. 1 (see Test Case No. 1)	Semisubmersible	Haltenbanken	1,000
6	Profile No. 2 (see Test Case No. 2)	Semisubmersible	Haltenbanken	1,000
7	Profile No. 3 (see Test Case No. 3)	Semisubmersible	Haltenbanken	1,000
8	Profile No. 4 (see Test Case No. 4)	Semisubmersible	Haltenbanken	1,000
9	Profile No. 1 (see Test Case No. 1)	Ship	Haltenbanken	2,000
10	Profile No. 2 (see Test Case No. 2)	Ship	Haltenbanken	2,000
11	Profile No. 3 (see Test Case No. 3)	Ship	Haltenbanken	2,000
12	Profile No. 4 (see Test Case No. 4)	Ship	Haltenbanken	2,000

- 1) All test cases in Table 5-1 are analysed for both ULS and ALS, and each limit state for Consequence Class 0 (tentative), Consequence Class 1 and Consequence Class 2, simply denoted ULS0, ULS1, ULS2, ALS0, ALS1 and ALS2.
The geometry and the size of the anchor plate are adjusted as appropriate for the assumed load and soil conditions, however, the anchor size as such is not assumed to influence the results of the reliability analysis and the code calibration.
- 2) The static and cyclic undrained shear strength of the clay are predicted for each case, accounting for the anchor size, load history and OCR. For the Gulf of Mexico, the soil data for the Marlin Field /11/ are the basis, supplemented with cyclic test data from the Drammen clay data base /12/ /13/. For Haltenbanken, the undrained shear strength is modelled as Drammen clay. The coefficients of variation (CoV) derived from extensive data bases like those for Marlin clay and Drammen clay may not be representative on their own for use in the calibration of the design code, and these CoV's have been replaced with values that are judged to be more representative for offshore design situations. In the calibration it is assumed that an adequate soil investigation has been carried out following recognised industry practice.
- 3) Details of the platform, the taut mooring system (TMS) and the mooring line data are provided in Appendix A of /7/.
- 4) For definition of OCR, $s_{u,0}$, Δs_u , k_I , k_2 , k_3 , k_4 , z_i see Section 3.2.



5.2.2 Pilot reliability analysis

Preceding the full-scope reliability analysis a pilot reliability was carried out. The basic strategy was to make the pilot reliability analysis as complete as possible for a single set of boundary conditions, thus providing the possibility to identify which parameters govern the results of the reliability analysis and where emphasis should be placed in the planning of the more detailed analysis. Test case 3 in Table 5-1 was selected to provide the basis for the pilot reliability analysis.

As part of the pilot reliability analysis a parameter study was carried out with the objective to assess how the cyclic shear strength $\tau_{f,cy}$ is affected by the composition of the load history used in the calculation of $\tau_{f,cy}$. For the semisubmersible platform in 1,000 m water depth in the Gulf of Mexico environmental conditions the sea states were characterised with significant wave heights H_s of 10 m, 13 m and 16 m, respectively.

Based on this parameter study it is concluded that a significant wave height $H_s = 10$ m is most critical with respect to the cyclic loading effect, and this wave height is therefore used in the reliability analysis.

5.2.3 Reliability analysis

The objective with the proposed change of the code format, see Section 5.1.2, is to use only one partial safety factor on the anchor resistance, and for the purpose of the reliability analysis and code calibration the following expression for the anchor resistance R has been used

$$R = N_c \cdot s_c \cdot \eta \cdot s_{u,anchor} \cdot A_{plate} \cdot U_{cy} \quad (5.10)$$

where

N_c = bearing capacity factor of the clay

A_{plate} = equivalent area of the plate

s_c = shape factor for plate

η = empirical reduction factor

$s_{u,anchor}$ = average static DSS undrained shear strength $s_{u,D}$ over zone influenced by anchor

$U_{cy} = \frac{\tau_{f,cy}}{s_u}$ = cyclic loading factor

$\tau_{f,cy}$ = cyclic shear strength of clay for given line load history

s_u = intact undrained shear strength of clay, in this case = $s_{u,D}$

Eight of the parameters are modelled as stochastic variables:

$s_{u,anchor}$ average of intact undrained shear strength of soil over soil volume influenced by anchor, dependent on depth of anchor (for practical purposes expressed in terms of an auxiliary stochastic variable U_{su} , see below)



- η empirical reduction factor, accounting for effects of soil compressibility, progressive failure, load eccentricity, etc
- U_{cy} factor accounting for the effect of cyclic loading on s_u and on the predicted static anchor resistance R_S , assumed to be the same at all points within the zone influenced by the anchor.
- N_{eq} equivalent number of cycles of maximum amplitude representing the effect of the storm that leads to failure in cyclic loading
- U_R model uncertainty factor on the predicted anchor resistance,
- C_{OCR} factor on predicted OCR to represent uncertainty in OCR; used only for overconsolidated clay in two-layer profiles
- F_e the applied line load
- U_F model uncertainty factor on the line tension.

The average shear strength $s_{u,anchor}$ to be used in Eq. (5.10) can be expressed as a deterministic mean strength $s_{u,mean}$ plus a zero-mean random term $U_{su}\sigma_{su}$

$$s_{u,anchor} = s_{u,mean} + U_{su} \cdot \sigma_{su} \quad (5.11)$$

in which $s_{u,mean}$ is a function of the plate width W_F and the depth of the plate z_{plate} . Possible statistical uncertainties in the deterministic mean term $s_{u,mean}$ owing to limited data is assumed to be small compared to the uncertainty represented by the random term and is ignored.

The zero-mean random term is expressed as $U_{su}\sigma_{su}$, where σ_{su} denotes the standard deviation of s_u and U_{su} denotes a standard normally distributed variable. Sometimes data indicate that σ_{su} is proportional with depth, $\sigma_{su}=kz$, where k is a constant and z denotes depth. Sometimes the standard deviation is better represented as a fraction of the mean value $\sigma_{su}=\text{CoV} \cdot E[s_u]$, where CoV denotes the coefficient of variation.

For the two-layer profiles represented by test cases 4, 8 and 12 in Table 5-1, it is found more appropriate to model the uncertainty in the intact undrained shear strength by a coefficient of variation (CoV) referring to $s_{u,mean}$. For all other test cases, the formulation based on $\sigma_{su}=kz$ is applied.

Justification for the chosen distributions of the stochastic variables is given in /7/, with literature references, wherever possible.

5.2.4 Probabilistic Formulation

In a structural reliability analysis, the failure event must be expressed in terms of a mathematical function in a structural reliability analysis. Such a function is termed a limit state function, usually denoted by $g(\cdot)$, and should satisfy the following properties:

$$g(\vec{x}) \begin{cases} < 0, & \text{for } \vec{x} \text{ in the failure set} \\ = 0, & \text{for } \vec{x} \text{ on the failure boundary} \\ > 0, & \text{for } \vec{x} \text{ in the safe set} \end{cases} \quad (5.12)$$



where \bar{x} is a realisation of the vector of stochastic variables \bar{X} involved in the problem. There are usually a number of different possible formulations of the limit state function for any specific problem. In the present reliability analysis, the basic limit state function is taken as the difference between the anchor resistance r and the applied line tension f , i.e.

$$g(\bar{x}) = r(\bar{x}) - f(\bar{x}) \quad (5.13)$$

where the anchor resistance r refers to the *dip-down* point, where the mooring line intersects the seabed, and the load is the applied line tension at the same point. The small contribution to the pullout resistance due to the embedded part of the taut mooring line, estimated to be in the range 100 to 300 kN, is neglected in the reliability analysis, which is on the safe side.

When including the details introduced above, the limit state function from Eq. (5.13) may now be rewritten as

$$(5.14)$$

$$g(s_{u,anchor}, U_{cy}, U_R, \eta, C_{OCR}, N_{eq}, f_e, U_F) = r(s_{u,anchor}, U_{cy}, \eta, C_{OCR}, N_{eq}) \cdot U_R - f_e \cdot U_F$$

where the arguments of the g -function include all the stochastic variables envisaged for the analysis.

All the stochastic variables involved in this formulation are time-invariant. The applied line tension varies with time, but the time dependency is taken into account by applying the annual extreme value distribution of the line tension.

The annual probability of failure may then simply be expressed as the probability mass associated with the failure state

$$P_f = \int_{g(\bar{x}) < 0} f_{\bar{X}}(\bar{x}) d\bar{x} \quad (5.15)$$

where $f_{\bar{X}}(\bar{x})$ is the joint probability density function of the stochastic variables involved in the limit state function.

5.2.5 Code calibration

As a basis for the code calibration the following three consequence classes are considered, all applicable for both ULS and ALS:

- 0 Tentatively, CC0 is reserved for platforms which are evacuated in severe weather, and are at a safe (large) distance from adjacent platforms and pipelines. (CC0)
- 1 Failure is unlikely to lead to unacceptable consequences such as loss of life, collision with an adjacent platform, uncontrolled outflow of oil or gas, capsizing or sinking (CC1).
- 2 Failure may well lead to unacceptable consequences of these types (CC2).

For these three consequence classes the prescribed target annual probabilities $P_{F,t}$ of failure are 10^{-3} , 10^{-4} , and 10^{-5} , respectively. The reasoning behind the target levels is given in /7/

The probability of failure is calculated for a series of values of the plate depth. For each limit state, consequence class, and design case, the plate depth corresponding to the required target



probability $P_{F,t}$ is found by interpolation on these results. It may be denoted by $z_{plate}(P_{F,t})$. The characteristic resistance at this depth is then $R_C[z_{plate}(P_{F,t})]$ from Equation (5.1). An estimate of the partial safety factor γ_m for an individual design case is simply given by

$$\gamma_m = \frac{T_d}{R_C[z_{plate}(P_{F,t})]} \quad (5.16)$$

The calculation is organised differently when calibrating over the whole set of design cases. The calibration for one limit state and one consequence class is considered. A trial value of γ_m is then chosen initially. The plate depths required to satisfy the design equation may then be denoted $z_{plate,i}(\gamma_m)$ for each of the i design cases. The corresponding probabilities $P_{F,i}(\gamma_m)$ are obtained by interpolation on the reliability results.

A penalty function is defined as

$$p(\gamma_m) = \sum_{i=1}^{12} (P_{F,t} - P_{F,i}(\gamma_m))^2 \quad (5.17)$$

where $P_{F,t}$ denotes the target failure probability and $P_{F,i}$ denotes the achieved failure probability of the i th design case among the twelve. It is noted that this penalty function penalises under-design more than overdesign. The sought-after optimal material factor γ_m is obtained as the solution to the following minimisation problem

$$\min_{\gamma_m} \sum_{i=1}^{12} (P_{F,t} - P_{F,i}(\gamma_m))^2 \quad (5.18)$$

which is expressed in terms of the defined penalty function and which implies an overall minimisation of the deviations of the achieved failure probabilities from target.

The results of the partial safety factor calibration according to the above procedure are presented in Table 5-2. The partial safety factors for load, γ_{mean} and γ_{dyn} , shown in brackets, are for this calibration set equal to the values prescribed in /1/. For CC0 tentative values have been assumed, since this consequence class has not been subject to calibration before.

Table 5-2 Calibrated partial safety factor γ_m for anchor resistance

Limit State	ULS			ALS		
Consequence Class	0	1	2	0	1	2
γ_{mean} (prescribed)	(1.00)	(1.10)	(1.40)	(1.00)	(1.00)	(1.00)
γ_{dyn} (prescribed)	(1.10)	(1.50)	(2.10)	(1.10)	(1.10)	(1.25)
γ_m	1.36	1.42	1.39	0.71	0.99	1.29

It is noted that the achieved failure probabilities show some variability over the scope of the code as represented by the 12 test cases, although these failure probabilities are the result of a minimisation of this variability. One goal of the code calibration is to develop partial safety factors that lead to as uniform a safety level as possible, see more about this in Section 5.2.6 following.



5.2.6 Recommended further work

The calibrated partial safety factors γ_m for anchor resistance speak for themselves, however, it should be noted that the optimisation that leads to their determination implies a variability in the achieved failure probability over the scope of code as represented by the 12 defined design cases. Although the partial safety factors in Table 5-2 result from a minimisation of this variability, an investigation of the achieved failure probabilities indicates that the achieved safety level is not quite as uniform as desirable.

In the future, one might therefore want to either refine the code format or reduce the scope of code in order to obtain a more uniform safety level. An investigation has shown that the safety level will become more uniform if the test cases defined for a ship on Haltenbanken are removed from the scope of code, leaving the scope of code represented by test cases defined on the basis of semisubmersibles only. A similar improvement may be obtained if the characteristic soil strength value becomes redefined from its present value equal to the mean to some lower-tail quantile.

One may also improve the calibration and make the design code more robust by adding more test cases, e.g. covering more environmental conditions, more water depths, but one will always be constrained by the budget available. In the present project, the budget does not allow more work to be done, but the information obtained from the reliability analysis has given more insight into relative importance of the different variables for the safety of plate anchors.

A future follow-up of the work reported herein may also focus more on interpretation of the results with the objective to learn more about what causes the variability in the achieved failure probabilities by thoroughly investigating each test case. This may indicate how much advantage there will be in modifying the definition of the characteristic resistance to take explicit account of the variability in soil properties at the chosen site.

It should also be borne in mind that the target safety level 10^{-3} has been introduced at a late stage as a result of the practice in the Gulf of Mexico, but at this stage this safety level is not well enough documented for inclusion in a future revision of DNV RP-E302 /1/. If this is of interest, more work needs to be done, which would be a possible work task in a follow-up phase of this project.

5.3 Design issues for plate anchors in clay

5.3.1 General

It has been a recognition from the very start of this project that plate anchors cannot be designed without due consideration of the anchor installation effects. The report on design issues for plate anchors in clay /2/ therefore addresses not only the design code, but also the effect of keying and rotation of the anchor before it is in the position for acting as a component of a mooring system.

For information about plate anchors, reference is made to the anchor characterisation reports, one for drag-in type plate anchors /3/, and one for push-in type plate anchors /4/.

5.3.2 Design calculations

From an anchor design point of view, the code description in /2/ provides a rather complete step-by-step recipe for how to design plate anchors in clay. The ultimate objective with the anchor design is to determine, through calculations, the necessary penetration depth, z_{calc} , of the selected



type and size of plate anchor, which meets the safety requirements of the code. Some of the design issues may, however, be difficult to address properly in certain cases due to lack of adequate data. In such cases a conservative approach must be taken.

5.3.3 Target installation depth

The importance of verifying by measurements that the final anchor penetration depth satisfies the target installation depth is emphasised. The target installation depth z_t is defined as the calculated depth z_{calc} plus the keying distance Δz_k plus the failure displacement Δz_f , i.e.

$$z_t = z_{calc} + \Delta z_k + \Delta z_f \quad (5.19)$$

Both these depth corrections are expressed in fractions of the plate width W_F .

The keying distance Δz_k is the additional depth an anchor must penetrate in order to account for the potential loss in penetration depth due to anchor keying and rotation, which has the objective to create an approximately normal loading position of the anchor with respect to the mooring line tension direction.

The keying distance Δz_k is normally the most significant correction of the two, but this will be dependent on anchor type and installation method.

For push-in type plate anchors /4/ the keying distance Δz_k is defined herein as the vertical displacement required for the plate to open the keying flap, plus the additional vertical displacement associated with the rotation of the anchor towards the "normal loading" position.

Tentatively, the keying distance may be set equal to

$$\Delta z_k = (0.75 \pm 0.25) \cdot W_F \quad (5.20)$$

for plate anchors equipped with a keying flap. Without a keying flap the keying distance may double.

For drag-in plate anchors /3/ the keying distance, defined as the loss in penetration depth due to rotation of the anchor after installation, is to a large extent dependent on the anchor installation direction relative to the in-service loading direction. For the STEVMANTA type for example, installed in the direction of the mooring centre, Δz_k may in certain cases be almost negligible, since the anchor may already after installation be close to the desired position. If the anchor is installed away from the mooring centre, which is the normal installation direction for the DENLA anchor, the anchor may have to rotate up to 90 degrees to reach the most efficient position to resist loads in the direction towards the mooring centre.

A second type of correction accounted for by z_t is associated with the anchor failure displacement, Δz_f . Tentatively, it is recommended to assume, based on experience, that the failure displacement can be set equal to

$$\Delta z_f = (0.3 \pm 0.1) \cdot W_F \quad (5.21)$$

Both these depth corrections should be accounted for in the specification of the target penetration depth of the anchor. The failure displacement is of significance particularly when the anchor is penetrated into a stiff layer underlying a softer layer. In such cases one should also be aware of



the effect of overloading the anchor, which may lead to a significant reduction in the anchor resistance, as discussed in /2/.

5.3.4 Keying load

From an anchor verification point of view, it is important to agree on how large the keying load T_k needs to be to ensure that the plate will behave satisfactorily during the service life, and tentative recommendations are given in /2/. The keying load, T_k , is the load that, combined with the actual lever arm, creates the necessary moment to rotate the anchor into an efficient and desired position. It may be necessary to measure the inclination of the anchor and use that as a criterion for when to stop pulling. This definition of the keying load is applicable to both push-in type and drag-in type plate anchors.

Tentatively, a keying load in the range

$$T_k = 0.50 - 0.75 \cdot R_s(z_i) \quad (5.22)$$

may be satisfactory to ensure an acceptable performance of the anchor.

5.3.5 Input data for anchor design

For the anchor design, the designer will need drawings of the selected type of anchor and the results from a quasi-static or dynamic mooring analysis addressing both limit states and the associated consequence classes. The line tension for the respective lines should be split into a mean component T_{mean} and a dynamic component T_{dyn} , as required by the design code /1/.

The scope and content of the soil investigation need to take into account the expected site specific conditions, so that the type of calculations required by the design code can be conducted. If adequate soil data cannot be provided, conservative assumptions will have to be made, see discussion in /2/.

5.3.6 Design code format

Although not necessarily a design issue, it is important for the designer to understand the differences between a partial safety factor format like the one prescribed in the DNV code /1/ and a total safety factor format like the one prescribed in API RP 2SK /14/. A discussion of the most significant differences between these two code formats is included in /2/.

5.4 Verification of the final penetration depth

It is emphasised that the final penetration depth of a plate anchor must be verified by suitable and reliable measurements. Per date, no such reliable methods exist, but all the anchor manufacturers are working on instrumentation systems suitable for their respective anchors.

After initial installation, a push-in plate anchor /4/ will be in an almost vertical position and the actual depth of the plate below the seabed can be measured with reference to the stick-up of the suction follower in the case of the SEPLA anchor, or by reference to the Guide Tube in the case of the PADER anchor. For verification of the final penetration depth, separate measurements will have to be carried out, e.g. using the initial installation depth as a reference for measuring the change in depth due to keying and rotation. The development of such systems is still in the development phase.



For drag-in type plate anchors, different means for measuring the penetration depth have been adopted. One common way of doing this is to use an installation wire with depth markings, which can be observed by an ROV, when the wire is tensioned after installation in connection with anchor rotation into an efficient position with respect to the direction of the line tension. Other means to control the anchor penetration depth is offered by the Anchor Tracker from Bruce Anchor /15/, which so far has been used mainly for tracking and recording the anchor penetration path.



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